UAV Concept of Operations for High Altitude Autonomous Earth Science Missions

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1.0 Introduction

The UAV Sector Roadmap states that "100% Autonomy" is a key goal for the Vehicle Systems program within 15 years. However, it does not provide detail with respect to
a. How this will "functionally" be achieved, and
b. Quantifiable metrics to gauge success.

In order to define quantifiable metrics for the UAV sector, a process has been initiated with two tasks. First, a concept of operations (Con-ops) document has been developed with detailed descriptions of two representative science missions. The Con-ops leads, in turn, to a functional requirements document that will guide the development of intelligent, autonomous systems.

This document is the Con-ops document. It is focused strictly on the near- term (5 yr) goals of the program. It includes sections on Mission Definition, Flight Phase Requirements, and Mission Metrics. Whereas the focus is on high altitude missions meeting Earth Science Enterprise goals, a low altitude mission and a multi-aircraft mission, in which a low altitude UAV complements the task of the high altitude UAV, are also described.

2.0 Mission Definition

Within NASA, the Earth Science Enterprise has long sought to use Unmanned Aerial Vehicles (UAVs) for science and application missions to complement other measurement platforms, including manned aircraft and satellites. There are key science issues for which the data required are not obtainable from other platforms. These include high altitude atmospheric composition measurements and earth surface events in inaccessible places or over long periods of time.

UAVs are potentially capable of providing unique data gathering opportunities as a result of their operational characteristics. Compared to manned aircraft:
- UAVs can be flown in dangerous situations, because there is no pilot or scientist on board.
- UAVs with long endurance can stay aloft and loiter during an emergency, monitoring the situation.
- UAVs with long range capability can be launched from a remote location, or flown to a remote location.
- UAVs can fly long duration, dull missions, such as mapping or for diurnal measurements, without inconveniencing pilot or crew.
- UAVs with high altitude capability can fly safely over weather and above air traffic.
- UAVs can be flown through toxic plumes for in situ sampling.

Compared to satellites:
- UAVs can fly to precisely selected locations at precisely selected times, and loiter as long as needed.
- UAVs can carry interchangeable high resolution imaging instruments.
- UAVs are recoverable for maintenance and upgrades of sensor and communication systems.

Compared to both satellites and manned aircraft, UAVs also have the potential of lower operating costs. Automation is a key enables to low-cost operations as human labor and launch costs are minimized/

2.1. Flight Phase Requirements

Several representative UAV Earth Science missions have been considered in detail. Three are presented here to illustrate the phases of operation, with emphasis on those activities, which either require or would be greatly enhanced by autonomous operation.

This document does not address all possible Earth Science missions or platform capabilities. Several which have been suggested by reviewers and which might be treated in more detail at a later date include:

- *UAV swarms*
- *persistence provided by rotating aircraft on and off duty*
- *air-to-air refueling*
- *small hand or vehicle-launched UAVs*
- *lighter-than-air airships*

2.1.1 High-altitude atmospheric composition measurements.
Scientific questions related to global climate change center around the changing composition of the atmosphere. Answering these questions requires data from the Earth's surface to the stratosphere and at all latitudes from the poles to the equator. Whereas NASA scientists have been able to gather valuable insights from measurements taken from the ER-2 and other platforms, these measurement tools are not ideal for obtaining a complete data set. A comprehensive set of measurements requires ease of reaching all latitudes, greater duration at altitude, and the ability to fly vertical profiles. In addition, real-time analysis of the *in-situ* composition would allow greater measurement productivity. This capability would allow real-time redirection of the flight path to the locations of greatest interest. It is possible to imagine a scenario in which scientists on the ground redirect the sampling probe (UAV with instruments) in geographic coordinates or to carry out a vertical scan. In the future, it might be more ideal for intelligent systems incorporated in the payload to redirect the platform to follow composition profiles.

Typical Mission: investigate the tropical cirrus cloud physical properties and formation processes for successful modeling of the Earth's climate.

Track vortex from satellite, identify filament target, monitor trace gases maximums to guide flight trajectory, monitor filament evolution over multiple diurnal cycles. Horizontal surveys (thousand of miles) with vertical profiles (0 –30 km) to determine (chemical and thermodynamic) structure. Revise flight plan to investigate emerging targets of interest (aerosol loading in clouds, mountain waves promoting stratospheric mixing), monitor atmospheric profiles with limb sounder at constant sun angle (fly terminator). Investigate structures in fine detail with expendable probes (dispensed from a mother-ship). Guide observations of atmosphere based on changing in-situ and satellite data. Avoid threatening weather and traffic. Return when mission complete. A representative profile for an atmospheric mission is shown in Figure 1.

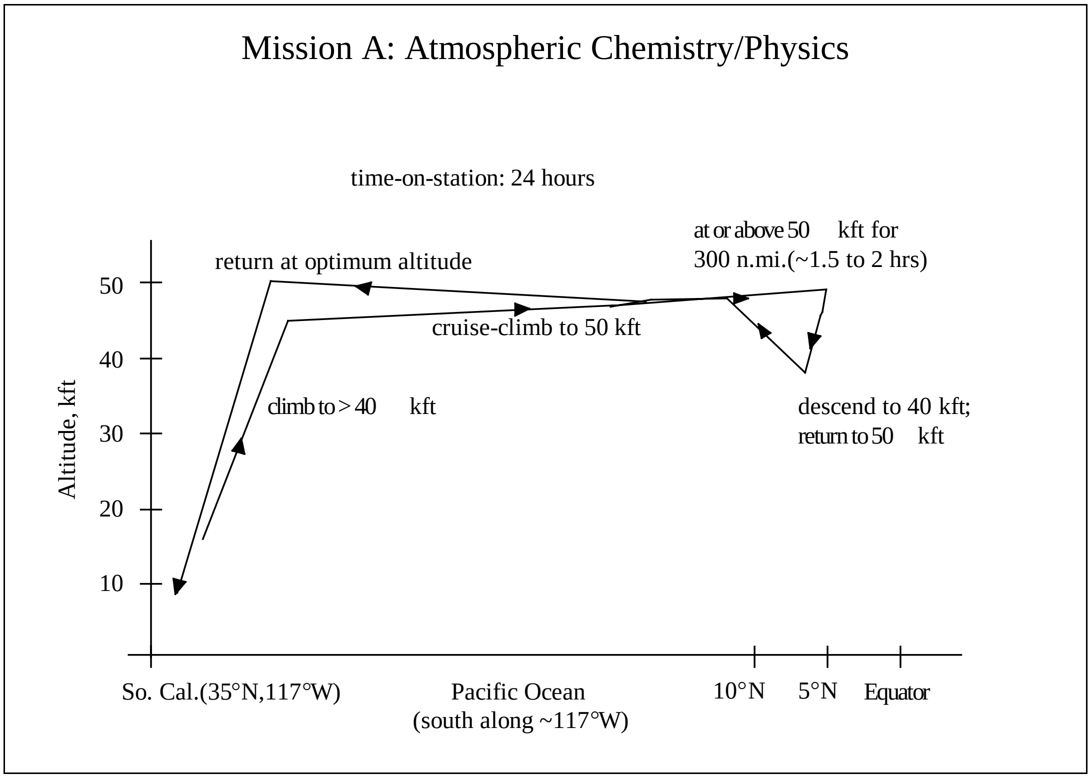

Figure 1. Flight profile for an atmospheric composition mission

Day in the Life of an atmospheric composition mission

A day in the life of an atmospheric sensing mission, including pre-flight and mission execution activities, is described here for the Collaborative Information Portal (CIP), the aircraft operator, and the aircraft system, including payload.

[As defined in the Functional Requirements Document: "The CIP provides personnel participating in the UAV mission with an interface to the payload systems, and to any external data sets, personnel, or sources of information necessary for the accomplishment of that mission. The CIP affords the means to visualize, observe and interpret data obtained by the payload; to visualize, observe and interpret mission-related data from sources external to the UAV system; to direct the payload systems (and indirectly the UAV); to communicate with other team members; and to integrate sensing goals into mission planning." The onboard autonomous executive would execute the plan, along with performing other basic tasks associated with flying the vehicle, including payload-directed flight. Capabilities include contingency management, in the event of unobtainable or conflicting goals, and coordination with other intelligent system specialists. one of which is an intelligent maneuvering (outer-loop) system capable of incorporating planning and decision-making models to give the vehicle goal directed self-reliant behavior, enable time-critical re-planning and execution adaptation to compensate for unexpected internal and external conditions, or various mission-specific science related findings.]

Preflight

For the CIP, preflight planning begins 3 hours before launch, providing data acquisition objectives, data acquisition priorities, and scheduling priorities. The CIP is used to develop an experiment plan, and to request a flight plan meeting the input objectives from the Planning Executive.

During the preflight period, the Aircraft Operator is responsible for the following activities: initiating an automated preflight check, updating divert options, carrying out a flight planning review, determining airworthiness and flight safety, authorizing the mission plan within constraints, and filing the Flight Plan. The operator will then launch the aircraft.

Mission execution

During the mission execution phase, the CIP carries out information-related activities including: confirming instrument readiness , confirming aircraft data availability, monitoring mission progress, initiating the measurement plan (follow pressure/temperature gradients) and updating satellite models with in-situ data, determine back trajectories, and follow up wind to local maximum, conducting vertical profiling between 65,000 to 30,000 (Upper Troposphere /Lower Stratosphere.

The aircraft (AC) system includes instructions to autonomously fly the aircraft according to flight plan, perform Detect, See and Avoid (DSA), avoid weather, and provide emergency response, if necessary. The AC system also responds to the mission Planning Executive to address mission tactical goals. It must respond to a dynamic environment to accomplish the mission by considering atmospheric conditions (including weather, targets and constraints), Air Traffic Control (separation and special needs), and new or revised mission objectives communicated from the CIP. In addition, the AC system checks sensor status (data QA, acquisition complete, engineering status). The AC system monitors AC status, including any elements of risk. Finally, the AC system performs predetermined post-flight operations and checks.

During the mission, the payload system carries out “smart data acquisition.” Elements include following a data acquisition plan that allows re-planning, using reconfigurable sensors for some measurements, monitoring data quality, delivering data in real time (if required), generating and distributing data products, and monitoring sensor system health and status.

During mission execution, the Operator or Mission Commander, has the following responsibilities: monitor aircraft health and mission safety, review dynamic mission planning, respond to aircraft emergencies, and finally, to recover the aircraft.

2.1.2 Disaster monitoring mission with Wildfire as example

UAVs with long duration loitering capability are ideal for monitoring hazardous or disastrous events on Earth’s surface. These could be natural events such as hurricanes, floods, volcanic eruptions or wildfires. They could also be man-made events such as toxic releases, traffic problems or terrorist activities. The common characteristics of the data gathering are the need to reach the event location, the ability to loiter more or less in place over the event (but out of the way), and the capability to receive and send data to other locations. UAVs have been proposed for wildfire observation because they meet these needs. (See UAV FiRE website: http://geo.arc.nasa.gov/sge/UAVFiRE/uavpayload.html.)

One important aspect of a wildfire observation mission is the ability to send images to fire commanders on the ground in near-real time. Another is the ability to move to other locations, as multiple fires usually occur during fire season. Whereas a UAV could be directed from the ground to change locations, or pre-programmed to scan selected coordinates to search for fires and then loiter if fire is detected, it could also be directed by satellite observations such as the MODIS fire mapper.

Typical Mission: Monitor western US, identify new Wildland fires, based on satellite and UAV observations, report fire status, request additional observational support, predict fire behavior.

Track air to ground lightning strikes from satellite to identify potential fire targets, prioritize potential targets based on risk to people and property to guide flight trajectory, investigate and report fires over multiple diurnal cycles. Revisit as needed. Horizontal surveys (FL250)(thousand of miles) with vertical profiles (to 5000 AGL) to monitor at fine resolution. Manage flight plan to optimize observation of cloud free images. Manage fire observations to establish perimeter, fire temperature, and provide real time imagery to fire fighters. Provide communications net to fire fighters as needed. Revise flight plan to investigate emerging targets of interest (satellite, onboard sensors, public spotters), Map fires extent, temperature rate of spread, for fire management, assess burned area for post fire restoration efforts. Communicated fire perimeter location to local incident Commander. Investigate structures in fine detail with expendable probes (mother-ship). Provide guidance for unmanned sire suppression aircraft to extinguish fire. Avoid threatening weather, terrain and traffic. Return when mission complete.

A representative profile for the disaster monitoring mission is shown in Figure 2. The ultimate time-on station requirement is multiple days, but 24+ hours is expected in the near term.

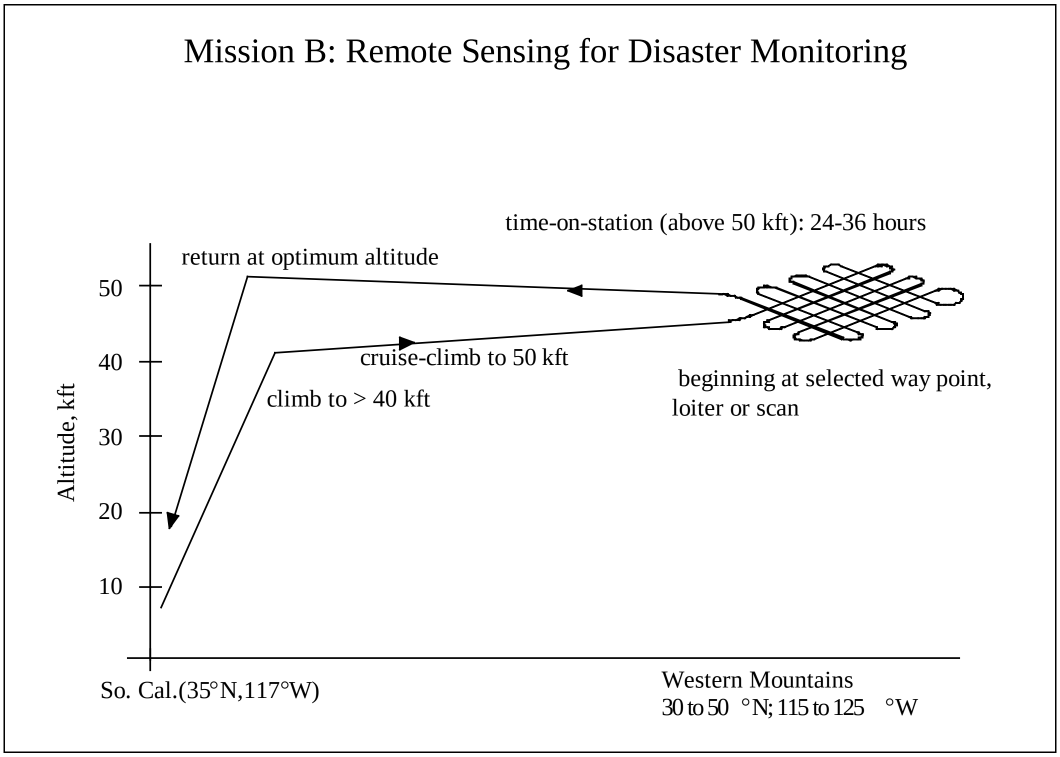

Figure 2. Flight profile for an atmospheric composition mission

Day in the life of wildfire response mission:
A day in the life of a wildfire response mission, including pre-flight and mission execution activities, is described here for the Collaborative Information Portal (CIP), the aircraft operator, and the aircraft system, including payload.

<u>Preflight</u>
For the CIP, preflight planning begins 3 hours before launch, providing data acquisition objectives, data acquisition priorities, and scheduling priorities. Significant input from the US Forest Service, or other land management/fire response agency is expected at this point. The CIP is used to develop an experiment plan, and to request a flight plan meeting the input objectives from the Planning Executive. The flight plan may need to address constraints imposed by fire-suppression activities.

During the preflight period, the Aircraft Operator is responsible for the following activities: initiating an automated preflight check, updating divert options, carrying out a flight planning review, determining airworthiness and flight safety, authorizing the mission plan within constraints, and filing the Flight Plan. The operator will then launch the aircraft.

<u>Mission execution</u>
During the mission execution phase, the CIP carries out information-related activities including: confirming instrument readiness, confirming aircraft data availability, monitoring mission progress, initiating the monitoring plan (considering priorities, fire risks) and updating satellite observational data, identify observational needs.

The aircraft (AC) system includes instructions to autonomously fly the aircraft according to flight plan, perform Detect, See and Avoid (DSA), avoid weather, and provide emergency response, if necessary. The AC system also responds to the mission Planning Executive to address mission tactical goals. It must respond to a dynamic environment to accomplish the mission by considering atmospheric conditions (including weather, targets and constraints), Air Traffic Control (separation and special needs), and new or revised mission objectives communicated from the CIP. In addition, the AC system checks sensor status (data QA, acquisition complete, engineering status). The AC system monitors AC status, including any elements of risk. Finally, the AC system performs predetermined post-flight operations and checks.

During the mission, the payload system carries out "smart data acquisition." Elements include following a data acquisition plan that allows re-planning, using reconfigurable sensors for some measurements, monitoring data quality, delivering data in real time (if required), generating and distributing data products, and monitoring sensor system health and status.

During mission execution, the Operator or Mission Commander, has the following responsibilities: monitor aircraft health and mission safety, review dynamic mission planning, respond to aircraft emergencies, and finally, to recover the aircraft.

2.1.3 Low altitude science missions and disaster monitoring using Vertical Take-off and Landing platforms

In addition to high altitude, long endurance (HALE) UAV missions, there are opportunities for low altitude, short endurance (LASE) missions as well. These could be independent missions or coordinated with HALE missions. Fixed or rotary-wing UAVs can be deployed locally to an incident and are highly maneuverable.

The major advantage is that they require little or no take-off or landing site preparation. One representative platform is the vertical take-off and landing (VTOL) vehicle, of which there are several autonomous models. Autonomy is a benefit for dynamic route planning. Another opportunity is found in the possibility of coordinating multiple vehicles of different capabilities and operating in different timescales, speeds, altitudes, etc.

Representative missions include:

- Antarctic science, in which a LASE UAV flies short data-gathering flights over land (imagery or environmental measurements) from the deck of a science vessel cruising off-shore.
- Nap-of-the-earth measurements over forests
- Detailed, up-close fire monitoring (described below)

Typical Mission:
A scenario integrating fixed-wing HALE and rotary-wing LASE vehicle classes is as follows: The HALE mission proceeds essentially as detailed above. Emerging fire locations are identified and the UAV is tasked to investigate them, as well as monitoring known incidents. As incidents

warrant (initially defined and coordinated by ground personnel, but potentially automated – e.g. a fire is growing rapidly in steep terrain, with forecast for dry winds) LASE UAV teams are deployed from the regional fire center or from devolving fires to the incident commander. This deployment could take as long as 12 hours; the HALE UAV would continue to monitor the incident on regular flyovers.

Upon arrival of the LASE UAV, it would be deployed to provide close-in mapping and data from the fire perimeter, starting from the last-known HALE data. Depending on the scale of the LASE UAV, these missions could also include fire suppression activities, delivery of supplies to hand crews, etc. This low-level capability, combined with the asset being dedicated to the local incident, would provide unprecedented real-time knowledge of the fire behavior. Additionally, the all-weather, day-night capabilities of the LASE UAVs, and their ability to operate in difficult terrain, would allow the incident commander to deploy these assets in conditions that are normally proscribed for manned aircraft. The mission is shown schematically in Figure 3.

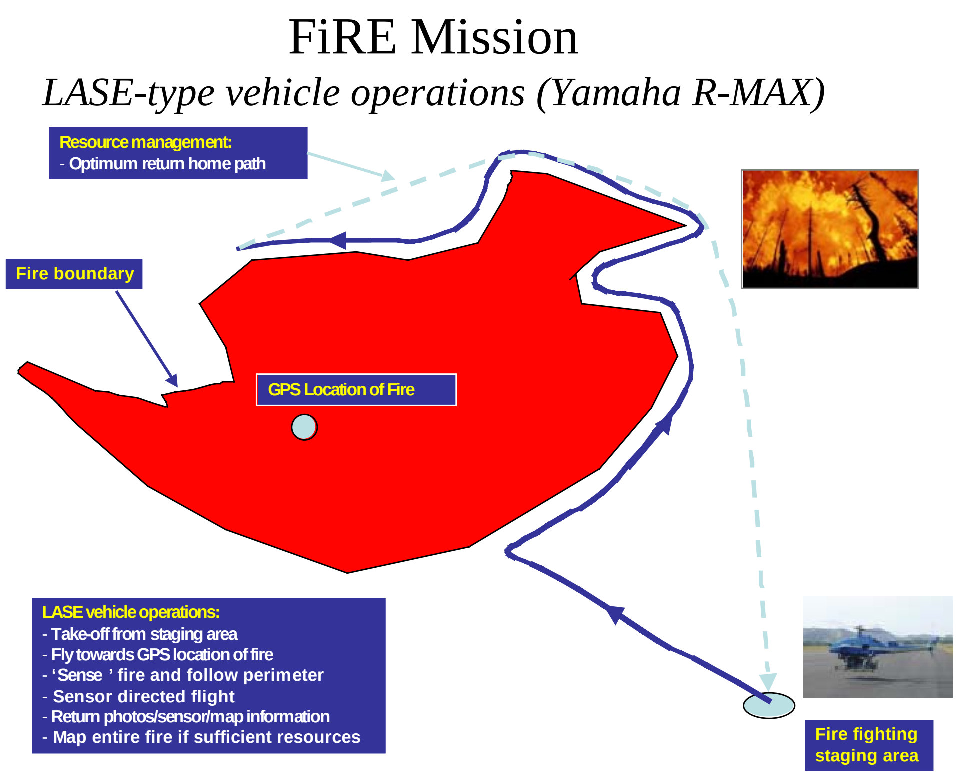

Figure 3. Flight path for LASE fire mission

Day in the Life of a LASE Mission

A day in the life of a low-altitude short-endurance (LASE) mission, including preflight and mission execution activities, is illustrated here for the Collaborative Information Portal (CIP), the aircraft operator and the aircraft system.

Preflight
For the CIP, preflight planning begins 1 hour before launch, providing data acquisition objectives from the HALE observer, data acquisition priorities from the Incident Command Center (ICC), and scheduling priorities, also from the Incident Command Center. The CIP is then used to develop an experiment plan, and to request a flight plan meeting the input objectives from the Planning Executive.

The VTOL is assumed to be available on site. During the preflight period, the Aircraft Operator is responsible for the following activities: initiating an automated preflight check, updating divert options, carrying out a flight planning review, determining airworthiness and flight safety, authorizing the mission plan within constraints, and filing the Flight Plan. The operator will then launch the aircraft.

Mission execution
During the mission execution phase, the CIP carries out information-related activities including: confirming instrument readiness, confirming aircraft data availability, monitoring mission progress, initiating the monitoring plan (considering priorities, fire risks) and updating HALE observational data, identify observational needs.

The aircraft (AC) system includes instructions to autonomously fly the aircraft according to flight plan, perform Detect, See and Avoid (DSA), avoid weather, and provide emergency response, if necessary. The AC system also responds to the mission Planning Executive to address mission tactical goals. It must respond to a dynamic environment to accomplish the mission by considering atmospheric conditions (including weather, targets and constraints), Air Traffic Control (separation and special needs), and new or revised mission objectives communicated from the CIP. In addition, the AC system checks sensor status (data QA, acquisition complete, engineering status). The AC system monitors AC status, including any elements of risk. Finally, the AC system performs predetermined post-flight operations and checks.

During the mission, the payload system carries out "smart data acquisition." Elements include following a data acquisition plan that allows re-planning, using reconfigurable sensors for some measurements, monitoring data quality, delivering data in real time (if required), generating and distributing data products, and monitoring sensor system health and status.

During mission execution, the Operator or Mission Commander, has the following responsibilities: monitor aircraft health and mission safety, review dynamic mission planning, respond to aircraft emergencies, and finally, to recover the aircraft.

2.2 Mission Metrics

Typical mission metrics for the three representative missions are described in this section. These metrics are meant to be illustrative; specific mission metrics would in actuality be defined in an Objectives and Requirements Document (ORD) and/or System Requirement Specification (SRS) document. *[For the high-altitude missions, we assume the platform is Altair, the long endurance*

UAV built by General Atomic – Aeronautical Systems Inc. (GA-ASI). For the low-altitude mission, we assume the RMAX ARP, a small Vertical Take off and Landing (VTOL) platform.]

2.2.1 Atmospheric sensing

Success criteria for the atmospheric sensing mission are based primarily on data gathered, i.e., useful data sets per flight. General metrics include volume of atmosphere sampled or continuous time on station.

Some specific requirements:

1. Ability to reach specific geographic coordinates: latitude, longitude, altitude; accuracy of these values in timed data records
2. Time on station, ideally over 12 hours
3. Resource monitoring to ensure safe return to base
4. Real-time data downlink
5. Over-the-horizon communications
6. Manual or payload-driven data acquisition strategies, based on target of opportunity
7. Close-the-loop on payload / sensors
8. Revisit or redirect instructions within minutes
9. Platform turn-around time, ability to fly on short notice (1 day)
10. Compatibility with or complement to other nodes in sensor web (e.g., satellites)
11. Acceptable to fly in unrestricted air space
12. Operational cost
13. Safety

Platform performance requirements for the atmospheric sensing mission are listed in Table 1. (Taken from Altair science plan,))

Table 1. Requirements for Mission A – Atmospheric Chemistry and Physics in the Tropics

Mission description	Three flights within 3 weeks (minimum)
Deployment site	Take off and land – Southern California (e.g., Edwards AFB, El Mirage,)
Flight duration	> 24 hours at altitude (above 50,000 ft)
Science objective	Characterize the chemistry and physics of the tropical tropopause
Payload instruments	*In situ* gas measurements (water vapor, ozone, a long-lived chemical tracer) radiometers (solar spectral flux), and meteorological parameters
FAA requirements	UAV operator to provide plan meeting requirements
NASA Safety Review	Required if NASA is involved
Horizontal flight track	Over the ocean and directly south from California to ~5ºN, return

Vertical flight profile	Above 50,000 ft between 10ºN and 5ºN; vertical dip of 10,000 ft at most southerly point
Integration requirements	instrument integration: Access to free stream air, possible ports or windows for radiometers.
Data downlink requirements	9600 bits/sec or current technology
Aircraft data required	Navigational and meteorological data sets synched to science data

In this mission, route replanning would be based on input from the on-board instruments. Therefore the composition (or perhaps temperature) analysis would provide guidance to the flight controls.

2.2.2 Wildfire monitoring mission

The success criteria for the hazard monitoring mission are timeliness and quality of data products to the ground, persistence or endurance on station and the ability to move as required to the next location.

Some specific requirements:

1. Ability to reach specific geographic coordinates while avoiding restricted air space: latitude, longitude
2. Time in flight, ideally 24hours
3. Resource monitoring to ensure safe return to base
4. Real-time data downlink
5. Over-the-horizon communications
6. Payload monitoring for specific imagery; target of opportunity / decision making based on imagery
7. Manual, payload-driven, or satellite-driven data acquisition strategies
8. Close-the-loop on payload / sensors
9. Revisit or redirect instructions within minutes
10. Platform turn-around time, ability to fly on short notice (12 hours)
11. Communications to ground command
12. Acceptable data rate of data products
13. Compatibility with or complement to other nodes in sensor web (e.g., satellites)
14. Acceptable to fly in unrestricted air space
15. Operational cost
16. Safety

Platform performance requirements for the fire monitoring mission are listed in Table 2. (Taken from Altair science plan.)

Table 2. Requirements for Mission B– Remote Sensing: High resolution fire monitoring of Western Mountains and Forests

Mission description	Available on short notice (within 12 hours) throughout fire season
Deployment site	Base of operations at El Mirage, Boise, Idaho or Las Cruces, NM
Flight duration	> 24 hours at altitude (above 42,500 ft)

objective	Obtain high resolution geo-located IR imagery for fire monitoring and real-time data downlink; coordinate with National Interagency Fire Center (NIFC)
Payload instruments	FiRE payload, including High resolution multi-spectral imager real-time video
Additional payload opportunities	Wescam Skyball, Synthetic Aperture Radar (SAR) for terrain mapping
NAS Coordination	UAV operator to provide plan meeting requirements. Operator and NIFC to coordinate actual flight plans
NASA Safety Review	Required; if NASA is involved
Horizontal flight track	Planned flight lines over unrestricted areas; then precise fire location determined by image interpretation or by Fire Service.
Integration requirement	instrument integration for downward looking imagers, in particular imaging ports
Data downlink requirements	0.45 Megabit/sec for AIRDAS; real-time video
Aircraft data required	Navigational and meteorological data sets synched to science data; aircraft video in real time

In this mission, precise location of the platform would be based on the fire image below. This feedback could be automated, or it might be controlled by users on the ground who are making use of the data. Route replanning would be driven by preset conditions, or assessment of the fire size from image data on the UAV, or external inputs, such as satellite data.

2.2.3 LASE Missions

The requirements include:
1. Vertical take-off and landing from spatially-constrained or at remote unprepared locations
2. Endurance up to 75 minutes
3. Up to 20 miles range, depending on radio communications
4. Real-time video, basic meteorology data, and other specific measurements, as required
5. Up to 15 kg payload capacity, depending on imaging system used
6. Altitude to 10,000 ft
7. Speed 45 to 75 knots

3.0 Acronyms & Abbreviations

AC	Aircraft
AGL	Above Ground Level
AIRDAS	Airborne Infrared Disaster Assessment System
ARP	Autonomous Rotorcraft Project
ATC	Air Traffic Control
CIP	Collaborative Information Portal
CONOPS	Concept of Operations
FAA	Federal Aviation Administration
FL	Flight Level
FRD	Functional Requirements Document
HALE	High Altitude Long Endurance
ICC	Incident Command Center
LASE	Low Altitude Short Endurance
MODIS	Moderate Resolution Imaging Spectroradiometer
NAS	National Airspace System
NASA	National Aeronautics & Space Administration
ORD	Objectives and Requirements Document
OTH	Over-the-horizon
QA	Quality Assurance
SAR	Synthetic Aperture Radar
SRS	System Requirement Specification
UAV	Unmanned Aerial Vehicle
VTOL	Vertical Take Off & Landing